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High Efficiency-Low Cost Powertrain for Urban Electric Vehicle

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Abstract

A Cooperation Project between: CR-ENEA "Casaccia" (Italian Governmental Agency for the Environment and Alternative Energy – Electric Vehicle division), Semikron Italy and University of Rome "Sapienza", started in 2006 to design a Full-Electric City-Car with the lowest possible specific consumption and using the technology which showed the best cost/performance ratio.
The result is an High Efficiency Dual-Feed City-Car (4kW Permanent Magnet Electric Motors, one in each Front Wheel). The P.M. Motors are powered by two Custom Specific SEMIKRON Power MOSFET Modules, which use the proprietary "Pressure Technology" and are controlled by Digital Signal Processors (DSPs). No gearing, neither mechanical coupling are necessary. Battery Pack during tests and races were Lead Acid, boosted by Ultracapacitor system to improve performances. UltraCapacitor Units, are mounted according to [1], [2]. In this paper has been demonstrated that consumption per kilometer was reduced over 10% using this solution.
Tests have been certified in the ENEA Test bench and during the Formula ATA 2008 competition at the FIAT Research Centre Facility, where the Car won the Second Prize and proved the reliability.

Keywords: Electric City-Car, low cost, high efficiency, Double feed, Ultracapacitor.

1. Introduction.

This paper describes the results of a cooperation project between CR-ENEA "Casaccia", Semikron Italy and University of Rome "Sapienza".
Task of the Project, started in 2006, was to design and build up a Battery Vehicle (a Full Electric CityCar with total no-load weight <400kg) having a specific consumption <120Wh/km on ECE-15M Urban Cycle, and using the technology which showed the best cost/performance ratio in order to stimulate market and industry interest.

Original solutions like the use of Ultracapacitors bank according to [1] gave positive results in terms of performances, consumption and system reliability. All the tests reported in this paper were certified in the ENEA Test bench and during the Formula ATA 2008 competition at the FIAT Research Centre Facility, were the Car won the Second Prize and proved the reliability.

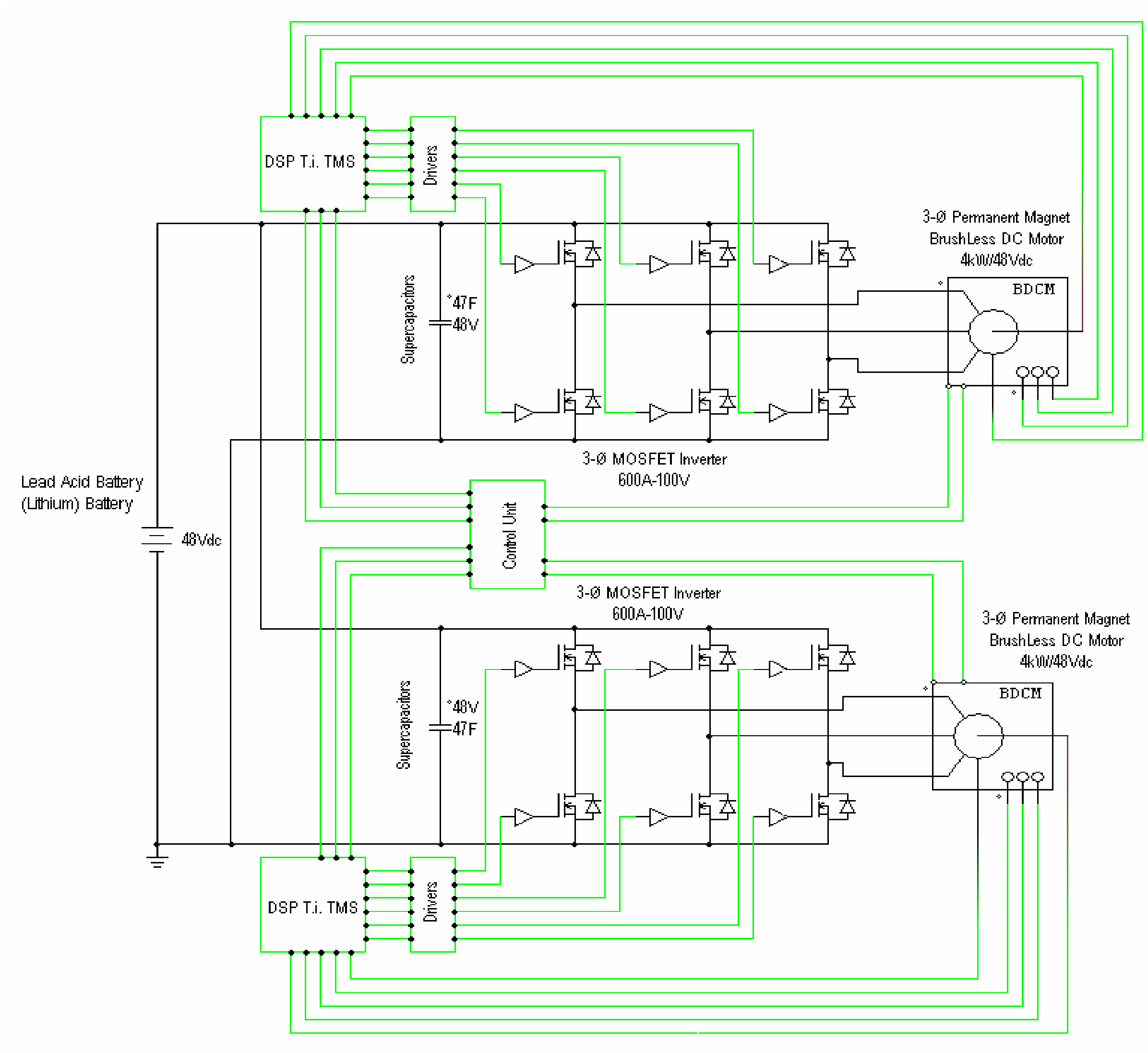


Fig. 1. Electric City-Car Architecture.

2. Electric PowerTrain.

The Electric PowerTrain structure of the above mentioned CityCar, is shown in Fig. 1, and is described herebelow. Any single part of the Electric PowerTrain is then detailed in the following sub-sections.
According to Fig. 1, the Electric PowerTrain of the developed CityCar is a typical double feed structure which uses Permanent Magnet Brushless Motors and separated PowerMOSFET Inverters and Control Units. The Power Supply uses a $48V_{DC}$ Battery Pack (mandatory voltage level for these Vehicles) and a splitted Dual Ultracapacitor bank in order to be extremely efficient during the regenerative braking. No DC/DC Converters [2] between Ultracapacitors and Battery Pack were used, according to [1]. In this way, the expected target in terms of costs, weight, dimension and reliability of the complete Powertrain have been achieved and can be considered adequate for this kind of Electric Vehicle. With the implementation of a simple Control with Dual Current feedback, via Microprocessor, an automatic ESP system has been implemented and the mechanical gearing has been eliminated.

2.1. Permanent Magnet Electric Motors.

The choice to use Permanent Magnet Brushless Motors (Fig. 2), were mainly related to their best Cost/Performance Ratio, but also to their Extremely High Capability to recovery Kinetic Energy from regenerative brakings.
Furthemore, the simple and reliable implementation of a current control, greatly semplify the complete

system giving high performances and reliability. Moreover, with the introduction of low-cost resolvers, the major drawbacks of these motors, related to the embedded Hall Effect sensors, can be overtaken.

Fig. 2. Permanent Magnet Brushless Motor.

In the following Table 1, are summarized the technical characteristics with the Typical and Max. values for the Electric Motors used in this application, produced by an Italian Manufacturer.

Table 1. P.M. Electric Motor Characteristics.

Characteristics	Values
Nominal Torque	65 Nm
Nominal Power	4,8 kW
Peak Torque	160 Nm
No Load max Speed	800 rpm
Nominal Voltage	48 V
Nominal Current	250 A_{RMS}
Max. Temp.	150 °C

2.2. MOSFET Power Modules.

Each Permanent Megnet Motor is powered by a Custom specific SEMIKRON MOSFET Power Module (Fig. 3).

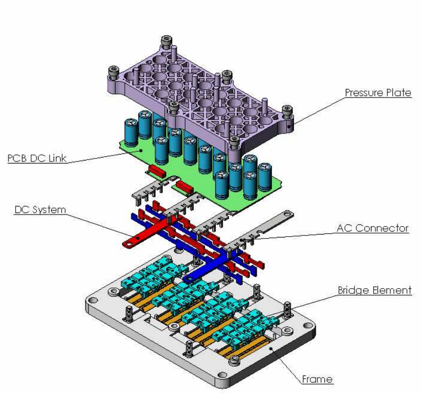


Fig. 3. Exploded view of the PowerMOS Module

This power module uses the latest "Pressure Technology" which assures high reliability and performances.

Furthermore, the use of two Power Modules gives also an important "redundancy" of the PowerTrain. This gives great sense of safety and reliability to the driver and finally it explodes the myth of unreliable Electric CityCars. In fact, several tests lasting many km, proved the full "driveability" of the cars even when one motor and/or one inverter failed.

Table 2. Power Module Characteristics.

Characteristics	Values
BV_{DSS}	100 V
I_D at 25°C	900 A_{DC}
I_D at 100°C	550 A_{DC}
$R_{DS(on)}$	750 µΩ
$R_{th(jh)}$	0,16 K/W
$T_{J(MAX)}$	175 °C

It must be noted that this impressive power is concentrated into very small dimensions 200x220x120 mm and light weight (2kg) giving a matchless power density.

2.3. Power Modules Control and Drivers.

As above mentioned, a simple Dual Current Feedback has been implemented to control the Trapezoidal B'less P.M. Motors and gives a very efficient Torque Control (see Fig. 4).

The control System exploits the computational characteristics of two 32 bits Digital Signal Processors (DSPs, TMSF2812 Texas Instruments). These two DSPs, controls the single motor torque and speed istantly giving the reference duty cycle at fs=18kHz to modulates the on-state of the Inverter's switches. In particular, special emphasis was dedicated to the control strategy in order to reduce the Inverters' switching losses, improving significantly the Power Train reliability.

The two DSPs are also used to manage the entire Vehicle signals and to work as "on board" Microprocessors.

Furthermore, special attention has been dedicated to the control strategy for the regenerative braking in order to be as symmetrical as possible and to exploit the great capability of the P.M. B'less Motors to recovers the Kinetic Energy.

Power modules driver were properly designed, since the peak current for the gate control could reach 12A. Complete Desaturation monitoring system and hardware fast intervention has been implemented to avoid any unwanted critical situation. Special attention was also dedicated to Electro-Magnetic Interference and noise levels.

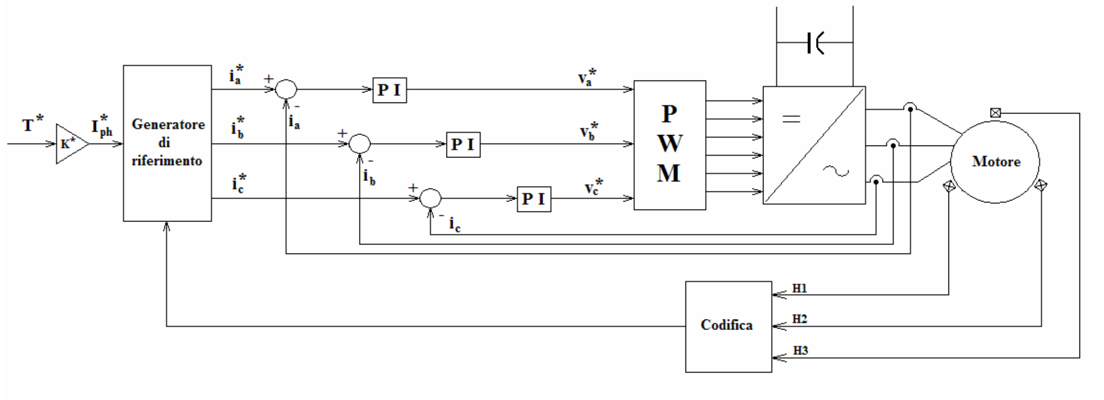


Fig. 4. Block schematic for the current control implementation.

2.4. Batteries and Ultracapacitors.

A Lead Acid Battery system has been used for this Electric Vehicle. In particular, in the following Table 3 are summarized the main characteristics.

Table 3. Battery Characteristics.

Characteristics	Values
Single Unit Voltage	6 V
Single Unit C_{10}	180 Ah
Total Battery Voltage	48-52 V
Nominal Energy stored	9 kWh
Total $ESR_{(DC)}$	6,3mΩ
Single Unit weight	32 kg

Furthemore to improve the efficiency of the system during the regenerative braking, a dual Ultracapacitor bank, were dimensioned according to [1] and listed in the following Table 4.

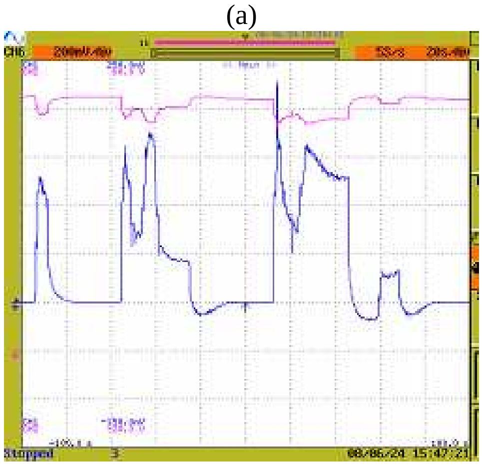
Table 4. Ultracapacitor Characteristics.

Characteristics	Values
Total Voltage	48,6 V
Total Capacitance	47 F
ESR(DC)	6,8mΩ
Single Unit weight	14 kg

Problems of availability in short terms of this Ultracapacitors pack lead to use a different type of Ultracapacitors with limited performances (i.e. C_T=23F, ESR=14mΩ).
In spite of this problem, the tests carried out on the real vehicle with and without the ultracapacitor bank were quite impressive in terms of performance and efficiency.
The acceleration between 0-50km/h improved over 5s! Furthermore, global Vehicle Efficiency had an improvement of 11,1%!

Life-time Expectancy of the batteries cannot be obviously measured in short times. But, looking at the following diagrams (Figs. 5.(a) and (b) which compare an ECE15-M Cycle of the present Citycar with Ultracapacitors and without Ultracapacitor), we can expect positive results.

(a)



(b)

Fig. 5.(a) Citycar without Ultracapacitor during ECE15-M Cycle. Fig. 5.(b) Same Citycar with Ultracapacitor during the same cycle

2.5. Power Train Assembly.

The complete Powertrain assembly as shown in Fig. 6 and described in the sub-sections 2.1. to 2.4., has been carried out by University of Rome "Sapienza" and an Italian OEM Company.

A transparency view schematic diagram is shown in Fig. 6.

In this picture, the positions of the PowerTrain sub-systems are quite evident. In the left side is shown

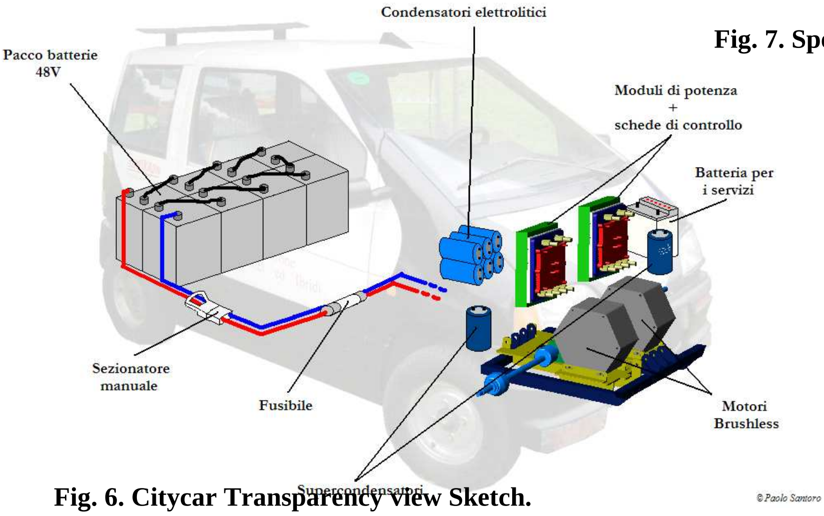


Fig. 6. Citycar Transparency view Sketch.

the battery pack (8x6V/180Ah), then are visible the Electrolityc caps, the two Ultracapacitors banks are sketched in the lift and right side in the front of the Vehicle. The Power Electronics and related control are incredible small and thanks to their efficiency are totally cold, so that there is no need of fan or liquid cooling semplifying the system and reducing costs. Finally the two motors (in exagonal shape are depicted in the centre of the front side Vehicle). Therefore, the assembly of this system is very fast and simple (and then cheap) and requires no huge investments (a simple workshop without any special tools would be enough to complete the assembly).

3. Test bench results.

The first tests were carried out in ENEA CR "Casaccia" Facility, in the automatic Electric Vehicle Bench Test.

Tests were based on the ECE-15M Urban Cycle, according to the international standards. During these tests were monitored the Power in DC and AC side, the Energy consumption and the Powertrain Efficiency. In the following figures Fig. 7. and Fig 8. the Vehicle speed and Torque at wheels were measured during the tests on standard

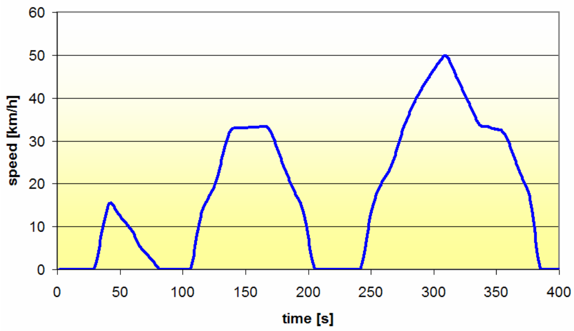


Fig. 7. Speed measurement at ENEA bench test

Cycle ECE15-M at ENEA Bench Test and also the Energy consumption.

In the following Table 5, are reported the results that we got from bench test session.

Finally, in Fig. 9, are shown respectively: Measurement at ENEA Bench Test. Battery current (green) reached a max of 230ADC and peak of 322A. Battery voltage (blue) was 56V max. Peak of the Motor phase current (red) reached 470A; Energy consumption (cyan) during this test was 108,3 Wh/km.

Table 5. Test results at ENEA bench Tests.

	Values
Max. speed	75 km/h
Max. torque at wheels	250 Nm
Energy consumption on ECE-15 Cycle. (MAX); [min]	(109), [92] Wh/km
Acceleration	1,75 m/s^2
Braking (kW), [Wh]	(6,7kW), [6Wh]

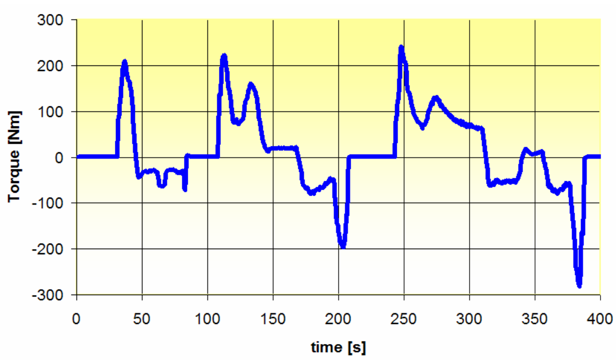


Fig. 8. Torque at wheels measured at ENEA test.

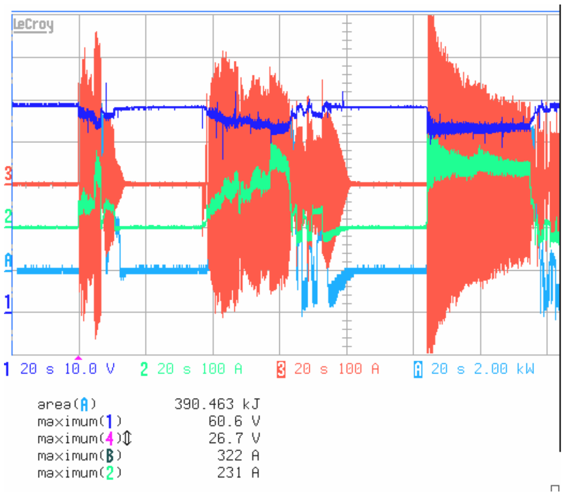


Fig. 9. Measurement at ENEA Bench Test. Battery current (green) and voltage (blue); Motor phase current (red); Energy consumption (cyan).

4. Race results.

The performances were tested and certified during the Formula ATA event (Fig. 10 and 11), held in Orbassano (at the Fiat Research Centre facility) from October 1st to October 4th 2008.

Fig. 10. Citycar during the competition.

The data we got from the ENEA Bench test, were confirmed on the field.
Moreover, we observed a significative reliability, easy "driveability" and even better performances than standard Internal combustion Engine cars.
The data we got from the races are summarized in the following Table 6, whilst the official results of the competition is reported in Table 7.

Fig. 11. Second place prize-giving.

Table 6. Citycar performances during race.

	Values
Max. speed	74 km/h
Range on specific laps	132 km
Energy consumption on sigle Lap	72 Wh/km
Slope	16%
Acceleration	1,7 m/s^2
Braking (kW), [Wh]	(10kW), [7,5Wh]

Table 7. Official race results.

2nd Place in the Cat. "B" Electric Vehicles (Vehicles < 400kg including Scooters).	
Endurance * (30 laps 2km each between 35-45km/h avg speed with no stop).	60 km
Slope	16%
Acceleration	1,7 m/s^2
Short Lap Pursuit	2nd place
Global Efficiency (excluding rechearg system)	72,8%
Long Lap Pursuit	1st place
AutoCross	2nd place

* the only Vehicle that completed the total laps with no stops.

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